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Anomalous MIS 7 sea level recorded on Bermuda

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Highlights

- New U-series dates for coral fragments confirm a MIS7 age for emergent, Belmont Formation, marine deposits on Bermuda
- New sedimentary evidence reliably establishes the elevation of relative palaeo-sea-levels
- First description of widespread Quaternary faulting in Bermuda
- We challenge the concept of Bermuda as a stable "tide-gauge" for Quaternary sea-level.

Three new U-series ages from coral fragments found in the Belmont Formation of Bermuda fall in a range of ~198 ka to ~ 196 ka. These late MIS 7 ages are consistent with those of ~201 ka and ~199 ka measured in a previous study. The disputed interpretation of the Belmont Formation as a unit that is allostratigraphically distinct from subsequent MIS 5e deposits, of the Rocky Bay Formation, is vindicated by a minimum age of 196 ±3 ka for the total of 6 coral fragments it has yielded. Emergent marine deposits of the Belmont Formation include sedimentary lithofacies that are considered to be reliable relative sea level indicators. Prominent among these is a facies representing the "beach step": a feature that develops sub-tidally, directly at the base of the swash zone. From this facies, and others preserved along 6 km of Belmont Formation coastal exposure, it is concluded that MIS 7 relative mean sea level reached +4.5 m, and likely peaked at or above +6.0 m, relative to present sea level at Bermuda. Lower MIS 7 sea level positions that are evidenced and that have been quoted, in the past, are considered transitory positions, not maxima. The MIS 7 sea-level elevations on Bermuda, reconstructed in this study, are well above the majority of those reported from elsewhere in the world. This challenges the long-standing notion of Bermuda as a vertically stable "tide-gauge", but is consistent with glacio-hydroisostatic models which predict land-mass subsidence at intermediate field sites, such as Bermuda, at the end of long interglacials. However, because of evidence of instability at Bermuda in the form of seismic activity and faulting, which require further investigation, judgment is reserved on the global implications of this palaeo-sea-level anomaly.

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1 Introduction

1.1 Global palaeo-sea-levels at MIS 7

A compilation of early deep ocean oxygen isotope records by Porter (1989) (summarised from Shackleton and Pisias, 1985 and Martinson et al., 1987), indicated that ice sheet volumes were substantially reduced three times between 250 and 180 ka, at Marine Isotope Stage 7 (MIS 7), but not to modern levels. By this interpretation, and other interpretations of continuous data such as that of Bintanja et al. (2005), there were three periods during MIS 7 when eustatic sea level approached the present level, but did not exceed it. Three peaks in global temperature during the time span of MIS 7 are, also, evident from the deuterium profile, measured in the Vostok ice core, which is considered a proxy for Antarctic temperature (Petit et al., 1999). A potential fourth MIS 7 positive sea level oscillation, at ~185 ka, was reported by Henderson et al. (2006) based on U-series dating of sedimentation events on the Bahamas Banks.

Evidence from speleothem growth-records from Argentarola Cave in Italy indicates that relative sea levels at sub-stages 7.5, 7.3 and 7.1 peaked above -18.5m; with the lowest peak, at about -18m at sub-stage 7.3 (Dutton et al., 2009). This general pattern was corroborated by oxygen isotope and other data, which are subject to bathymetric controls, from the Red Sea cores (Rohling et al., 2009). These indicate that sea level at MIS sub-stages 7.5 and 7.1 may have peaked as high as -10 m relative to present sea level but that at MIS 7.3 fell well short. Muhs et al. (2002) provides a good summary of palaeo-sea-level data from emergent reef terraces at Barbados, New Guinea and Hawaii (far field sites). He notes that at least two MIS 7 mean sea level oscillations are inferred, which depending on the approach taken to correct for uplift, range from -20 m to a few metres above present sea level. Another comprehensive review of MIS 7 global sea level data from a variety of sources including reefs, speleothems and oxygen isotopes led Siddall et al. (2006) to conclude that after correction for uplift or subsidence, as appropriate at respective localities, eustatic relative sea level at each of the MIS 7 sub stages ranged between ~ -15 m and ~ -5 m.

Higher MIS 7 sea-levels are evidenced in the Mediterranean at Mallorca where "brackish" speleothems record a +4.9 m RSL (relative to present mean sea level) at 230 ka (Vesica et al., 2000); while at Sardinia, marine deposits dated by the optically stimulated luminescence method (OSL) at 186 ka have been associated with a +2.5 m RSL palaeo-sea-level (Andreucci et al., 2009). Correspondingly, Murray-Wallace (2002) and Muhs et al. (2011) and Muhs et al. (2012) describe coastal deposits and coral reefs of MIS 7 age, respectively, in southern Australia, southern Florida and the Antilles (Caribbean), which witness relative palaeo-sea-level maxima in the range of +1 m to +4.5 m RSL.

The data quoted above are not from parts of the globe which are assumed to be in an equivalent tectonic setting to Bermuda. Nor was any consideration given as to whether they might have experienced comparable isostatic adjustment to Bermuda, attributable to its imputed position on the "peripheral bulge" of a major ice sheet complex (Raymo and Mitrovica, 2012). The data are intended to represent a cross-section of sources from which a wide range of MIS7 eustatic sea levels have been inferred, and with which the relative sea level record at Bermuda can be compared.

1. 2 Bermuda palaeo-sea-levels at MIS 7

The carbonate archipelago of Bermuda, situated at 32.3° N, 64.8° W in the North Atlantic, occupies the south-eastern edge of a 26 x 52 kilometres submerged oval-shaped reef-rimmed platform, below which is the truncated Bermuda volcanic seamount. The islands are predominantly compsed of lithified Quaternary aeolian bioclastic calcarenites, or "eolianites" (Sayles, 1931), which accumulated in shore-parallel, hillocky dune ridges. The six allostratigraphic geological formations identified by Vacher et al. (1989) are, from oldest to youngest: the Walsingham Formation, The Town Hill Formations (Upper and Lower), the Belmont Formation, the Rocky Bay Formation and the Southampton Formation. They are separated by geosols, characterised as "solutional unconformities" by Land et al. (1967). Emergent shoreface and foreshore deposits - the focus of this study - are volumetrically minor, being restricted to narrow coastal outcrops. They are considered effectively contemporaneous with eolianites, of the same formation, which conformably overlie them. The association of dune building with sea level highstands has thus been made (Bretz, 1960; Land et al., 1964; Vacher, 1972).

In the Quaternary calcarenites of Bermuda, Land et al. (1967) identified phreatic water table cementation and a depositional “strandline” in the Belmont Formation of the south shore (Figure 1) at +2m RSL.

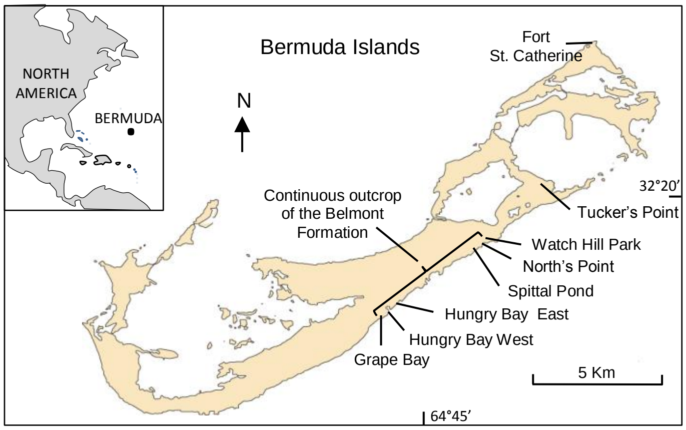


Figure 1. Bermuda Islands locality map.

They believed that this recorded the penultimate interglaciation, i.e. MIS 7. Subsequently, a thorough all-encompassing study of Bermuda’s palaeo-sea-level record was undertaken by Harmon et al. (1983); and on the basis of a marine layer within dated flowstone and four coral fragments from coastal deposits, they concurred that at MIS 7 eustatic sea level peaked at ~+2 m RSL at about 200 ka. They reported an older age of 262 +35 -27 ka for an *Oculina* fragment found at Grape Bay, but they questioned the accuracy of this age and did not associate it with the Belmont Formation or the penultimate interglacial. However, given the ~ 30 ka margin of error, this age could arguably be correlative with a marine transgression at a sub-stage of MIS 7. Subsequently, Muhs et al. (2002) reported late MIS 7ages of 199 ±2 and 201 ±2 ka for two *Oculina* fragments collected from the Belmont Formation, also, at Grape Bay.

Geological mapping of the island which culminated with publication of the Geological Map of Bermuda (Vacher, Rowe and Garrett, 1989) identified dozens of previously undocumented exposures of emergent clastic marine deposits. These were concentrated within the Belmont and Rocky Bay Formations, which on the basis of allostratigraphic interpretation were considered representatives of highstands at the penultimate and last interglaciations, respectively. Among the new finds were “beach bubble” fenestrae in Belmont foreshore deposits at ~+7 m at Watch Hill Park (Figure 1). Meischner et al. (1995) advanced an hypothesis of two Belmont marine transgressions peaking, respectively at + 1.5 m and +≥7.5 m RSL based on: 1) separation of two marine units by a vermetid-encrusted surface at Grape Bay; 2) measured elevations of sub-tidal bedding at Grape Bay; and 3) a “marine-eolian transition” at +7.5 m RSL at Watch Hill Park. Subsequently, Vollbrecht and Meischner (1996) presented evidence of meteoric phreatic diagenesis and coeval marine cement in the Belmont at Watch Hill Park ranging up to ≥ +8 m RSL (at the “beach bubble” locality). They made no assertions with respect to the age of the Belmont Formation.

Hearty and Kindler (1995) found no evidence of the +7.5 m RSL Belmont sea-level, reported by Meischner et al. (1995) and Volbrecht and Meischner (1996). They contended that, based on the interpretation of sedimentological features combined with Harmon et al.’s (1983) ages and amino acid racemization (AAR) dating of mollusks and land snails (Hearty et al., 1992), Belmont sea-levels peaked at ~0m RSL at ~240ka to ~230 ka, and at +2.3m RSL at ~210 to ~180 ka.

Hearty (2002) recanted on his previous conclusions with respect to the age of the Belmont Formation, citing an earlier failure: 1) to correct AAR data for the effect of prolonged interglacial warmth; and 2) to take account of potential re-working of corals with old ages (MIS 7) into younger (MIS 5e) deposits. He advocated that, consistent with the deep ocean oxygen isotope record (Shackleton and Opdyke, 1973), MIS 7 palaeo-sea-levels at Bermuda did not exceed current levels and that emergent marine deposits of the Belmont Formation were, instead, associated with an early MIS 5e highstand. He reasoned, accordingly, that a revision of Bermuda’s stratigraphy was in order, which entailed re-assignment of former Belmont Formation deposits, to a member of the Rocky Bay Formation (Figure 2), which is correlated with MIS 5 (Harmon et al., 1983). This new interpretation was re-asserted by Hearty et al. (2007).

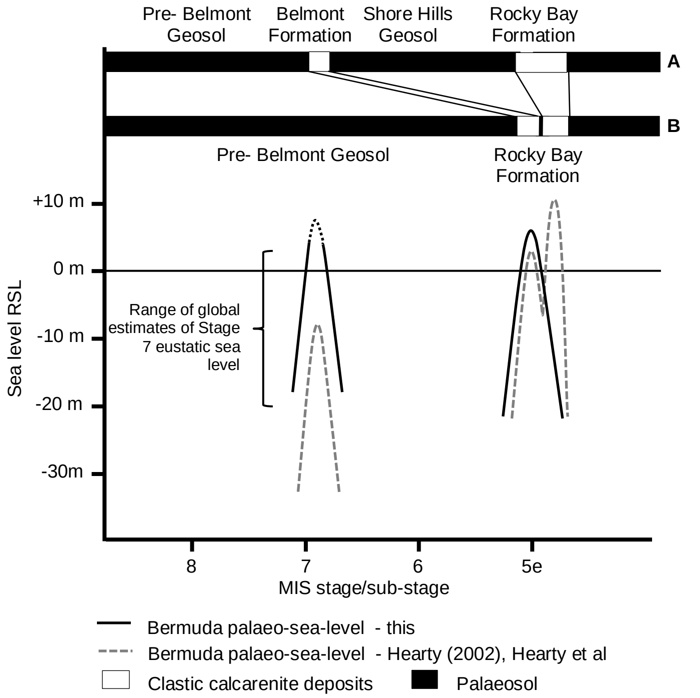


Figure 2. Mid to late Pleistocene stratigraphy of Bermuda in relation to palaeo-sea-level. The established consensus* version (**A**) includes the Belmont Formation deposited at a MIS 7 highstand. Hearty's (2002) version (**B**) re-allocates the "Belmont" deposits to the, MIS 5, Rocky Bay Formation and, correspondingly, downgrades the Shore Hills Geosol to an intra-formational colluvium. New age data, presented here, corroborates the former allostratigraphical model. * Sayles (1931), Bretz (1960), Land et al., (1967), Vacher (1972), Vacher et al., (1989), Vollbrecht and Meischner (1996), Vacher and Rowe (1997), Rowe (1998).

1.3 Objectives

In this paper we revisit the Belmont Formation of Bermuda, whose deposition at MIS7 (Land et al., 1967; Harmon et al., 1983) has been disputed by Hearty (2002) and Hearty et al. (2007), as noted above. We present new U-series dates for coral fragments collected from the Belmont Formation as well as new sedimentary and fossil evidence to reliably establish the timing and minimum height of at least one marine transgression associated with the Belmont Formation. Our approach is to provide objective information on a portion of the palaeo-sea-level record at Bermuda, which can best be achieved by avoiding the adoption of a firm position on the islands' tectonic or isostatic circumstances.

2. Lithofacies as palaeo-sea-level indicators.

The near-absence of growth position fossil corals in Bermuda is compensated for by the wealth of clastic depositional features, whose elevation at the time of their development was constrained by contemporaneous mean sea level. Twelve sedimentological lithofacies or sedimentary "structural facies" (Clifton et al., 1971) have been identified through field work undertaken in Bermuda over the last 4 years, principally within the Belmont Formation of the south shore (Figure 1). These lithofacies, their associations, stacking patterns and elevation of key features have been catalogued at more than 50 localities. Based on examination of modern equivalents and on published descriptions of analogous coastal deposits elsewhere in the world, these lithofacies have been attributed respectively to: the upper shoreface, the beach-foreshore and the beach-backshore.

Four examples of Belmont Formation depositional sequences are presented in Figure 3. Facies analyses show that, collectively, they represent a carbonate clastic environment in which prograding beaches transitioned, seaward, into aggradational shoreface sequences in response to a positive sediment budget and rising relative sea level. Transitory sea level positions are recorded, within these sequences, by sea-level indicator facies (**SIF**s). These are the facies that are considered to have particularly well constrained vertical relationships to coeval mean sea level.

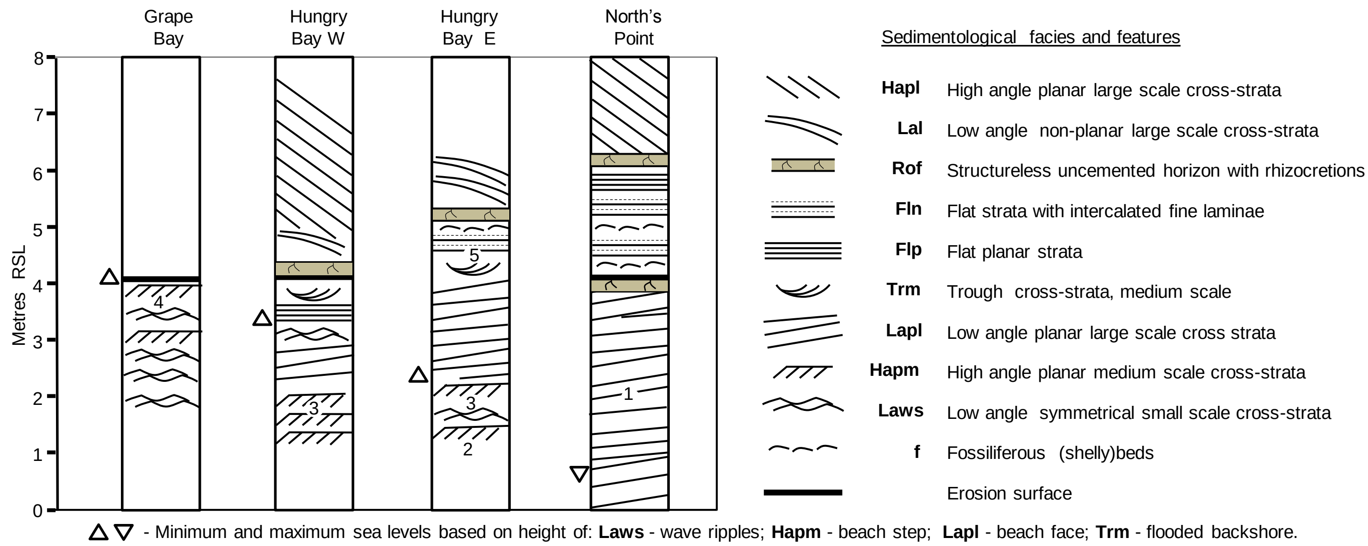


Figure 3. Examples of Belmont Formation facies sequences from Bermuda's south shore. The key sea-level indicator facies (**SIFs**) are considered to be: **Hapm, Lapl, Trm,** attributed, respectively, to the upper shoreface, foreshore and backshore environments (Figure 4). The SIFs at **1,2** and **3** record transitory positions of a generally rising relative sea level. Inter-tidal foreshore deposits at **1** are superseded, at the same or higher elevations, by sub-tidal shoreface deposits at **2,3** and **4**. The highest imprint among these sequences, at Grape Bay (4), records a ~+4.5 m RSL sea level. Backshore flooding by storms or high tides is evidenced by water-lain **Trm** and **Fln+f** facies (5)**.** A pause in, or reversal of, the trangression is represented by regressive **Rof**, **Lal** and **Hapl** sub-aerial facies.

Facies annotation breakdown: **Ha** - high angle cross strata (≥ 20°); **La** - low angle cross strata (< 20°); **Fl** – flat strata; **Tr** - trough shaped cross strata; **p** - planar strata; **Ro** - structureless; **w** - near symmetrical ripple cross strata; **s** - small scale cross strata set (< 5cm); **m** - medium scale cross strata set (5 cm – 1m) ; **l** - large scale cross strata set (> 1m).

Belmont Formation **SIF**s are: 1) High angle medium scale planar, seaward-directed avalanche cross-strata (**Hapm**); 2) Low angle large scale, seaward dipping planar cross-strata (**Lapl);** and 3) Medium scale tabular sets of trough cross-strata (**Trm**) . Through consideration of flow regimes and comparison with analogous facies that have been described in the literature, as well as through recognition of their spatial association with other facies, these have been interpreted as follows: **Hapm** represents the beach step or plunge step (Bauer and Allen, 1995; Dabrio et al., 2011) of the upper shoreface, equivalent to the "inner rough facies" of Clifton et al. (1971); **Lapl** represents the swash zone of the foreshore, equivalent to "inner planar facies" of Clifton et al. (1971); **Trm** (and associated **Fln+f**) represents shallow-water washover or tidal deposits of the beach backshore.
The respective elevation constraints on coeval sea level associated with the three key facies are summarized in Figure 4. These constraints were

Key sea-level indicator facies (SIFs)					
Facies	Symbol	Description	Associations	Interpretation	Mean sea-level Relative to top surface of facies
Trm		Tabular, trough cross-strata, small to medium scale.	**Trm** overlies prograded beach sequences.	Beach backshore - washover/tidal flats	- 2 to - 0.5 m
Lapl		Low angle seaward dipping, planar cross-strata, large scale.	**Lapl** either exhibits a truncated upper surface or is overlain by burrowed upper beach deposits. **Lapl** transitions seaward and down-dip into **Hapm.**	Foreshore - beach face	- 1.0 to - 2.5 m
Hapm		High angle seaward dipping planar cross-strata, medium scale.		Upper shoreface - beach step.	0 to + 1.0 m

Figure 4. Key sea-level indicator facies (**SIF**) of Bermuda's Belmont Formation. **Hapm** and **Lapl** are the products of wave action at the seaward front of a beach; whereas **Trm** developed in shallow flowing water which inundated the backshore during storms or at high tides. Their respective relationships to coeval mean sea level are inferred from modern equivalents in Bermuda and from analogous facies whose depositional environments have been reconstructed (by others) elsewhere in the world.

derived by observation and measurement of equivalent features on modern beaches of Bermuda where the sloping foreshore beach face (of the swash zone) and the beach step (of the upper shoreface) are habitually well developed. The beach step, or plunge step, is created by seaward directed backwash, along the seabed, at the base of the swash zone. Its existence as a "topographic step" was recognized by (Clifton et al., 1971). Its development, maintenance and migration under various states of the tide was described by Bauer and Allen (1995), who noted the importance of a backwash vortex in sustaining the ~20° avalanche face as detailed by Matsunaga and Honji (1983) and Larson and Sunamwa (1993). Reverse flow in the vortex is manifested as climbing ripple sets superimposed on the foresets, as commonly observed within **Hapm** of the Belmont Formation (Figure 5).

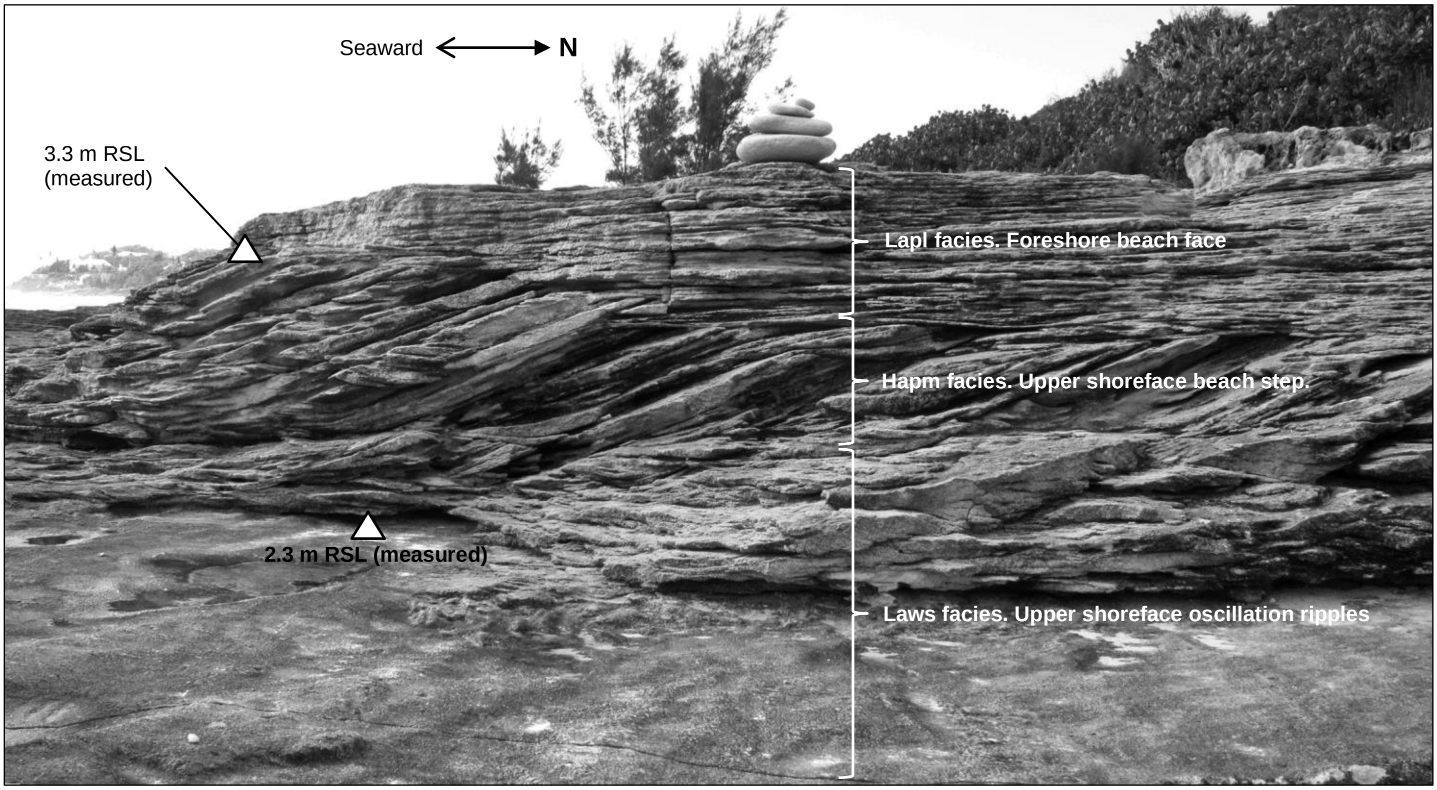


Figure 5. The **Hapm** facies in the Belmont Formation at Grape Bay. The sequence is interpreted as representing the progradation of a beach face (**Lapl**) and beach step (**Hapm**) over wave rippled upper shoreface deposits (**Laws**). Contemporaneous mean sea level stood at +3 to +4 m RSL. Not far to the west of this locality a +4 to +5 m RSL palaeo-sea-level is recorded by a similar sequence (Figure 7). The seaward increase in thickness of the **Hapm** facies is probably related to aggradation during beach progradation into slightly deeper water.

The distinctive characteristics of **Hapm** facies, and its inferred development as a beach step at a laterally and vertically constrained position on the shore, qualifies it as the foremost sea-level indicator facies (**SIF**) in Bermuda. Its existence other than at Grape Bay (where Meischner et al. (1995) described it as a "ramp") has never previously been documented in Bermuda, despite making an appearance at multiple localities and elevations from 0 m to ~+4 m RSL. The value of the beach step as a sea level marker, has been established by studies in Spain where small allogenic fluctuations in paleo-sea-level are manifested by vertical and lateral shifts of the **Hapm** facies in Miocene and Pleistocene coastal sandstone bodies (Roep et al., 1998; Dabrio et al., 2011; Dabrio and Polo, 2013). Notably, Dabrio et al. (2011) rejected the possibility that any beach steps in their study area had developed in association with storm surges, which is an important conclusion with respect to reliable interpretation of the mean sea level position. We agree that ambient swash zone conditions under which well-developed beach steps are known to be generated (Bauer and Allen, 1995) would not be replicated, at a higher elevation, at the height of a storm. Certainly, large storm surges and associated waves, of today, invariably erode and flatten Bermuda's beaches. The foreshore accretion that would be required to preserve beach step strata above current mean sea level is, thus, absent.

The low angle planar **Lapl** facies, interpreted as the beach-face, is a reliable **SIF**, albeit with a margin of error that is larger than that of the **Hapm** facies. This is because of the variability of its maximum elevation (at the berm crest) from +1.0 m up to +2.5 m RSL, associated with cycles of storm erosion and beach re-building, exhibited by "winter" and "summer" profiles. Also detracting from the precision of **Lapl**, as an **SIF**, is frequent evidence of its truncation and, thus, incomplete preservation, in Bermuda's Belmont Formation. Identification of the **Lapl** facies and **Hapm** facies are mutually corroborated where the former transitions down-dip, and in a seaward direction, into the latter (Figure 5).

As alluded to earlier, the Belmont Formation facies architecture attests to an episode, or episodes, in which beach progradation transitioned into aggradation in response to a rising sea level. **Trm** and the flat bedded shelly laminae of **Fln+f,** are manifestations of increased vulnerability of the backshore to inundation, as the marine transgression outpaced sediment supply and, possibly, reef growth. Larger waves and the related development of dissipative beaches may have exacerbated this vulnerability to intermittent backshore flooding, The **Trm** and **Fln+f** facies are typically found in direct vertical succession superposed on the **Lapl** facies . The tabular trough cross-beds of **Trm** record alongshore or seaward directed currents, sometimes bi-directional, characteristic of water flow at the top-end of the lower flow regime (Harms and Fahnestock, 1965), as would be expected when the backshore is flooded by high tides and/or by storm washover (there are no rivers in Bermuda), to an extent that is not witnessed in Bermuda today.

More information on the development of the facies architecture within emergent beach deposits of the Belmont Formation and on the method used for field-measurement of elevations (RSL) of features, such as **SIF**s, is provided in the Supporting Information.

3 Establishing ages

3.1 Provenance of dated coral fragments

Although the modern Bermuda Platform features a proliferation of biogenic reefs, including those of the vermetid cup variety in the nearshore (Thomas and Stevens 1991), only an occasional emergent, growth-position fossil coral has been reported in the literature (Harmon et., 1983). Their existence has subsequently been difficult to verify and, at this time, none are known from the extensive Belmont Formation outcrops of the south shore. As a consequence, it is not possible to use *insitu* corals as sea-level indicators. However, broken pieces of corals have been found within the upper shoreface and beach deposits of the Belmont Formation at Grape Bay and Spittal Pond. These coral fragments are from the genus *Oculina* which have been selected for ^{230}Th/U dating in previous studies (Ludwig et al., 1996; Muhs et al., 2002). They are 'clean', not incorporated into lithoclasts or covered by encrusting fauna and relatively unworn (Fig 6). In addition, the coral pieces are much larger than the sand particles of the calcarenite facies from which they were collected. Taken together these characteristics suggest limited reworking, with transportation that was short in distance and duration. This conclusion is consistent with the interpretation that the Belmont Formation deposits, from which the *Oculina* fragments were collected, represent progradational deposition associated with a high positive sediment budget when carbonate production was at a maximum. It is reasoned that, a prograded ancient littoral deposit which accumulated under these circumstances is likely to comprise bioclastic material predominantly from near-contemporaneous living organisms.

Successive limestone formations, in Bermuda, record episodes of carbonate productivity on the platform, at highstands, interrupted by lengthy glacial periods during which only solutional/pedogenic processes prevailed. Whereas conglomerates on erosional surfaces are likely contaminated by old material as a result of reworking, stratified aggradational or progradational calcarenite deposits are expected to yield clustered ages, that represent the time of deposition, and that are distinct from the ages associated with adjacent formations. Such circumstances are borne out by U-series age data from coral fragments, as well as amino acid racemization (AAR) relative age-data from marine mollusk shells. Dating of: 22 coral fragments from the Southampton Formation (Harmon et al.,1983; Ludwig et al., 1996; Muhs et al., 2002) ; 7 fragments from the Rocky Bay Formation (Harmon et al., 1983; Muhs et al., 2002); 5 fragments from the Belmont Formation (Muhs et al., 2002; and this study); and 4 fragments from a modern beach (Ludwig et al. 1996), in each case yielded a cluster of ages that are exclusively correlative with a single marine isotope sub-stage (Figure 6) . These findings were corroborated by 43 AAR ages from marine shells which clustered into three distinct "aminozones" corresponding to the Belmont, Rocky Bay and Southampton formations from which they were collected (Hearty, Vacher and Mitterer, 1992). This prompted the authors to conclude that "there is a striking agreement between the succession of aminozones and the relative ages implied by the mapped lithostratigraphy of the host deposits". Even where marine facies of successive formations are in direct contact, as at Grape Bay (see Figure 9), U-series ages yielded by the respective formations are grouped into two distinct clusters separated by more than 25 ka (Figure 6).

Such consistency in the correspondence of U-series age distribution with the established stratigraphy, supports the concept of a relatively short transport-time between the growth of an organism and accumulation of its skeletal remains in a deposit; and refutes any meaningful impact of reworking on substantive prograded or aggraded stratified calcarenites on Bermuda.

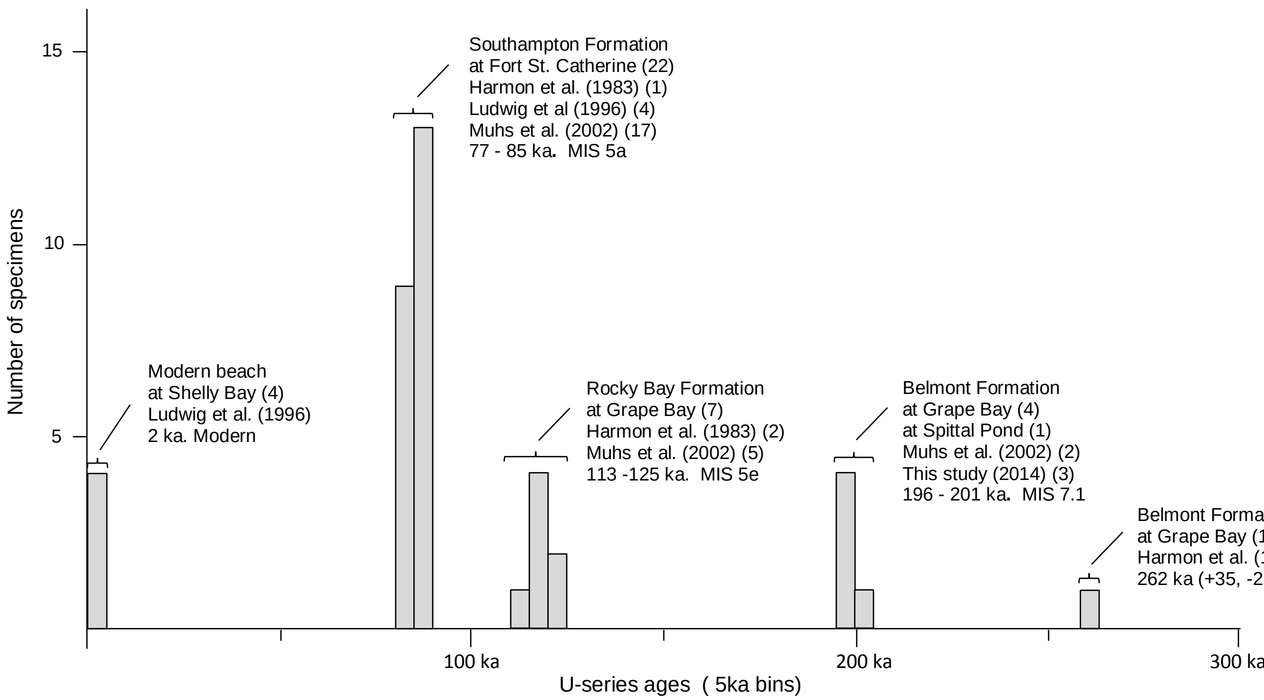


Figure 6. U-series ages of 35 coral fragments collected from progradational and aggradational foreshore and shoreface calcarenite deposits on Bermuda. Stated margins of error in the age measurements are < ±3 ka in all but three cases where they range up to ± 6 ka and in one case (the 262 ka age of Harmon et al., 1983) where it is > ±20.

3.2 U-series dating methodology

Three coral fragments of *Oculina* collected from the Belmont Formation at Grape Bay (2) and Spittal Pond (1) were prepared for U-Th dating, as follows: Coral surfaces, including septas, were carefully abraded using a diamond coated, rounded hand-drill bit to remove material that may have been exposed to diagenetic processes. Pieces of ~300 mg were then isolated using a circular diamond saw, ultra sounded in deionised water and dried down. They were then treated with a mixed ^{229}Th-^{236}U spike and dissolved in nitric acid, before refluxing in reverse aqua regia to remove all traces of organic matter and ensure sample-spike equilibration. Chemical separation of U and Th from the sample matrix followed procedures adapted from Edwards et al. (1986). Measurements of U and Th were performed by Nu-Instrument Multicollector-inductively coupled plasma mass spectrometer (MC-ICP-MS) at the University of Oxford. The following recently updated half-lives were used to compute the results in Table 1: 245,620 +/-260 a for 234U and 75,584 +/-110a for 230Th (Cheng et al., 2013). The modern sea water value of the ^{234}U/^{238}U activity ratio is 1.147 ‰ (Delanghe et al., 2002). For all three samples, the ^{234}U/^{238}U initial activity ratio is close to this value on the basis of known variability of past seawater ^{234}U/^{238}U ratios during the glacial-interglacial cycle (Stirling et al., 1998 and Esat et al., 2006). On the assumption that the Thompson et al. (2003)

model is applicable, corrections for diagenisis were attempted. Resultant “corrected” ages are slightly younger than the original ages (see Section 4.2).

4 Results

4.1 Palaeo-sea-level elevations

Some of the higher facies sequences of the Belmont Formation, as exemplified at North’s Point, Hungry Bay East, Hungry Bay West and Grape Bay (Figure 3), represent a transition from progradational to aggradational deposition in response to a marine transgression. Inter-tidal **SIF**s transition laterally, in a seaward direction, into sub-tidal **SIF**s, which may, in turn be stacked vertically. The facies architecture which developed at that time is similar to that described by Dabrio and Polo (2013) under analogous circumstances within the late Miocene carbonates of southeast Spain. The facies associations at Bermuda, collectively, evidence palaeo-sea-levels which ranged from close to present sea level up to several metres above it. The highest **Hapm** facies found so far, at Grape Bay, attests to a Belmont mean sea level at ~+4.5 m RSL (Figure 7).

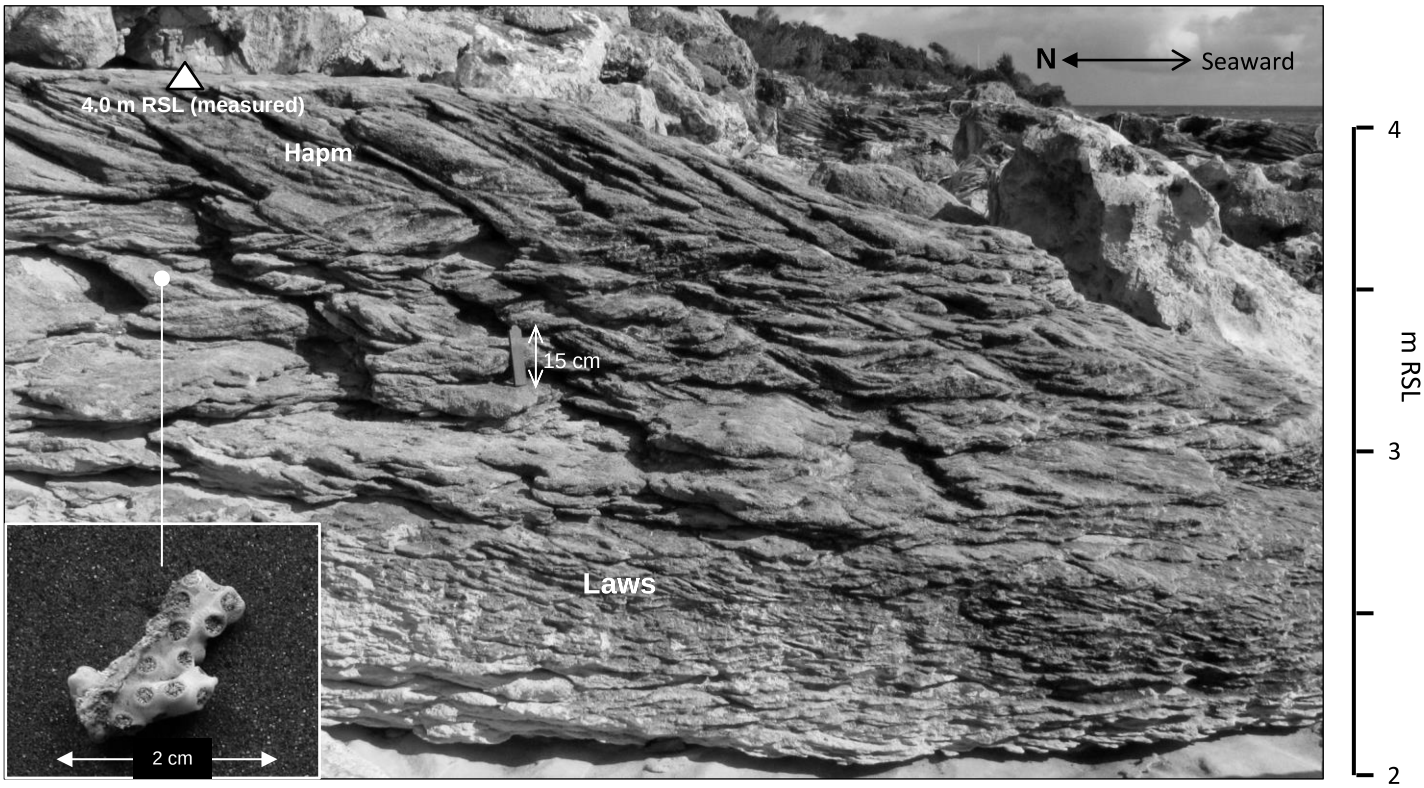


Figure 7. A facies sequence , at Grape Bay, that represents progradation of the beach step (**Hapm**) over oscillation ripple cross laminae (**Laws**) of the upper shoreface (interpetation confirmed by email communication with Cristino Dabrio 2012). Intervening between the two are medium scale cross beds (wave ripples) of the inner rough facies (Clifton et al, 1971). A palaeo-sea-level of +4.0 to +5.0 m RSL is inferred. *Oculina* fragment “C” (bottom left) which yielded an age of 197 ka ±3 ka was found, nearby, at the base of the **Hapm** facies.

Evidence of a higher, ≥+6m, palaeo-sea-level associated with the Belmont Formation is found at Watch Hill Park where **Lapl** (beach face deposits), shelly layers and incipient foredunes are elevated up to 2 m above their highest counterparts at other localities along the south shore (such as those of Figure 3). More conclusively, an erosional notch populated by in-situ sessile marine fossils at Watch Hill Park (Figure 8) is now attributed to submergence by a Belmont sea, which must have surpassed +6.0 m RSL. Earlier interpretations that the feature was a product of a subsequent Rocky Bay highstand were shown to be erroneous when a new exposure was revealed by storm erosion. The second notch is demonstrably onlapped by un-colonised Belmont **Lapl** facies. From this, it is inferred that a post-Belmont highstand was not responsible for the marine imprint in question. The fact that it is an aeolian calcarenite of the Town Hill Formation - the immediate predecessor of the Belmont Formation - which is notched and colonised, provides an upper age constraint for the highstand.

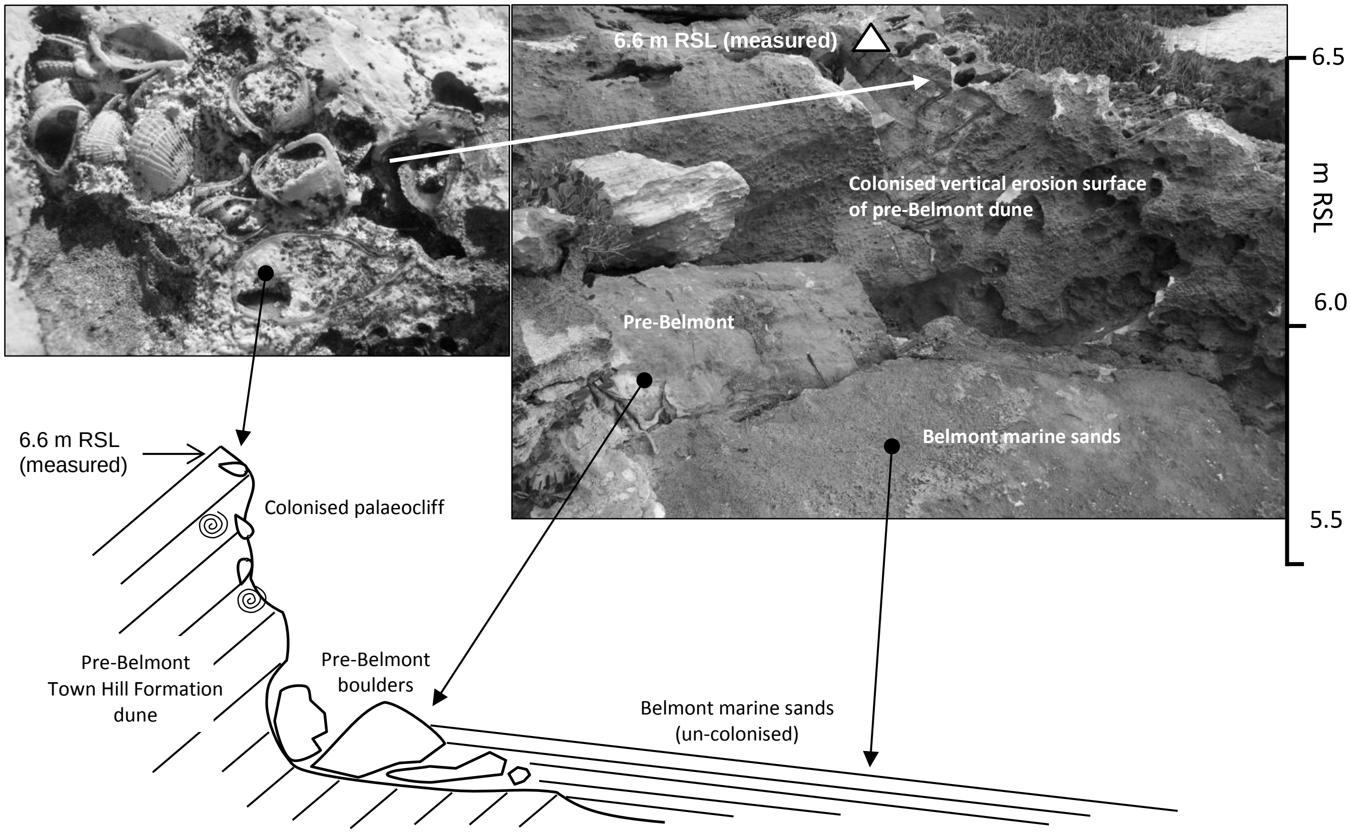


Figure 8. Emergent notch/palaeo-cliff, at Watch Hill Park, whose past partial submergence below mean sea level is evidenced by life-position bivalves (Brachidontes domingensis) and encrusting vermetid worms which would have occupied a high energy inter-tidal rocky shoreface. Boulders and marine sands which rest against the cliff are mapped as Belmont Formation marine deposits. Consistent with other evidence in the vicinity, such as high elevation phreatic cementation, these features are indicative of a Belmont highstand at of ≥ +6.0 m RSL.

Corroboration of an exceptionally high Belmont marine transgression is provided, again at Watch Hill Park, in the form of coeval phreatic cementation (associated with prolonged submergence) within Belmont calcarenites at ≥+7.0 m RSL, as reported by Vollbrecht and Meischner (1996).

4.2 Age of the Belmont Formation

As part of this study, three coral fragments were collected from the Belmont Formation for dating. One from Spittal Pond yielded an age of 196 ka ± 3 ka . Two from Grape Bay, 4.5 km to the east (Figure 1), which were found approximately 30 metres apart, both yielded ages of 198 ka ± 3 ka.. The small offset in the $^{234}U/^{238}U$ activity ratio suggests that the samples have suffered sufficiently limited diagenesis for us to state with confidence that the corals grew within the time span of MIS 7 (see Table 1). For the sake of completeness, a correction for diagenesis was made, and the resultant ages fall within the error bars of those initially calculated with the exception of coral fragment B which came in ~9 ka younger than the original value. If accepted, this would attribute growth of "B" - the youngest coral fragment in the group - to a period of climatic transition between 190 and 185 ka or to a very late MIS 7 episode of warming tentatively identified by Henderson et al. (2006). In any case, we continue to assert that a robust correlation has been made between growth of Belmont Formation coral fragments and the MIS 7 interglacial period.

Site	sample ID	Aliquote	^{238}U	$^{230}Th/^{238}U$	±	$^{234}U/^{238}U$	±	$^{232}Th/^{238}U$	±	Uncorrected age	err+	err-	Corrected age	err+	err-	$^{234}U/^{238}U_{initial}$	±
			ppm	activity ratio		activity ratio		activity ratio								activity ratio	
Spittal pond	Coral B	1	2.089	0.93221	0.00413	1.09458	0.00445	0.00000	0.00002	196.321	2.930	2.691	196.323	2.824	2.694	1.165	0.007
Grape Bay	Coral E	1	2.189	0.92759	0.00402	1.08720	0.00456	0.00005	0.00001	198.038	2.923	2.822	197.997	2.918	2.819	1.152	0.007
Grape Bay	Coral C	1	2.234	0.92683	0.00337	1.08572	0.00424	0.00027	0.00001	198.250	2.461	2.565	198.250	2.461	2.565	1.150	0.007
		2	2.160	0.89858	0.00226	1.08970	0.00360	0.00043	0.00004	197.692	1.938	1.806	197.573	2.042	1.953	1.150	0.005

Table 1. Ages of three Oculina fragments are provided versus the 1950 reference. 95% confidence intervals are quoted. Decay constants used are 9.1706 ∗ 10−6 yr−1 for 230Th, 2.822 ∗ 10−6 yr−1 for 234U (Cheng et al., 2013) and 1.55125 ∗ 10−10 yr−1 for 238U (Jaffey et al., 1971). Ages are corrected for detrital 230Th assuming it is scavenged from seawater with an atomic ratio of 232Th/230Th of 20000 (Robinson et al., 2004).

All three coral fragments were found near the base of the **hapm** facies at +2.5 to +3.5 m RSL. Since the Belmont Formation, by definition, includes no unconformities or other evidence of significant hiatuses equivalent to a full glacial stage, its MIS 7 assignment (based on coral dating) at one locality, where for example a +3.0 m to + 4.0 m sea level is inferred, can be extended to Belmont marine imprints, elsewhere, including those indicative of a ≥+6.0 m RSL palaeo-sea-level.

Two *Oculina* fragments previously collected from the Belmont Formation at Grape Bay by Muhs et al. (2002) yielded ages of 199 ±2 and 201 ±2 ka. One collected by Harmon et al. (1983), also from Grape Bay, had a reported age of 262 +35 -27 ka, which could conceivably represent an early or mid- MIS 7 highstand. To date, no fragments from corals whose growth could have occurred at an interglacial period other than MIS 7 have ever been found within demonstrable Belmont Formation deposits. The consistency of the five reliable ages, falling between ~201 and ~196 ka, is expected on the basis of a reasonable default assumption that the fragments came from corals which, in life, were near-contemporaries of the facies within which they were preserved. Taking into consideration the taphonomy of the coral fragments (see Section 3.1), we conclude that the U-Th ages are attributable to first cycle sediments contemporaneous with the depositional age; and that cross-formational contamination, invoked by Hearty (2002), is no longer credible.

There is agreement that the deposits traditionally assigned to the Belmont Formation, record a palaeo-sea-level of at least +1 m to +2.5 m RSL on Bermuda (Land et al., 1967; Harmon et al., 1983; Hearty and Kindler 1995; Vacher and Rowe, 1997; Hearty, 2002; and Hearty et al., 2007). What has become contentious is the elevation at which the associated palaeo-sea level peaked, and the age of these Belmont deposits. Based on the findings, reported here, and earlier research (Harmon, 1983; Muhs et al., 2002), it is re-asserted that the minimum age of the Belmont Formation of the south shore is correlative with late MIS 7.

5 Discussion

5.1 Disputed age of the Belmont Formation

In Hearty's 2002 article entitled "Revision of the late Pleistocene stratigraphy of Bermuda" he observed that "Bermuda's pre-eminent status as a global sea-level "tide gauge" is compromised and paradoxical when global views of MIS 5e and 7 highstands are considered". His concern was that a MIS 7 positive excursion of sea level (to above present level), as had apparently been recorded on Bermuda by the Belmont Formation, was incompatible with evidence of much lower MIS 7 sea levels found elsewhere in the world. By re-interpreting the Belmont Formation as an early MIS 5e deposit (part of a putative MIS 5e double peak) and merging it into the Rocky Bay Formation, as shown in **B** of Figure 2, he was able to resolve the "paradox". This was at the cost, however, of dispensing with a central feature of established Bermudian stratigraphy, namely the major allostratigraphic boundary, or solutional unconformity (Land et al., 1967), which separates the Belmont Formation and subsequent MIS 5 Rocky Bay Formation (Vacher et al., 1989). Prior to this proposition, the Shore Hills geosol, which records the unconformity at non-coastal outcrops, had been characterised as a "well developed red palaeosol" (Land et al., 1967), or "terra rossa soil" (Bretz 1960) with associated "solution pipes" (Vacher, 1972; Herwitz and Muhs, 1995) and was considered, to represent a "long interval of sub-aerial erosion" (Sayles, 1931) equivalent to a full interglacial period, correlative with MIS 6. Two coastal manifestations of the unconformity that is correlative with the Shore Hills soil are shown in Figures 8 and 9.

Hearty once subscribed to the view that deposition of the Belmont Formation was associated with events at an MIS 7 highstand which surpassed present sea level (Hearty et al., 1992). His 2002 revision necessitated compression of the time gap between the Belmont Formation and Rocky Bay Formation into the time span of MIS 5e (Figure 2). We contend that the undisputed MIS 5e age of the Rocky Bay Formation, coupled with MIS 7 ages associated with Belmont sediments (Harmon et al., 1983; Muhs et al., 2002; and this study), refute this shortened time scale. We also believe that Hearty's (2002) re-characterisation of the Shore Hills geosol as an intra-formational "soil-like" colluvial deposit can be attributed to his focus on low elevation coastal exposures, as referenced in his article. At such localities, it is evident that the mature Shore Hills geosol was destabilised or reworked by the MIS 5e marine transgression and stripped away (Figures 9 and 10) or locally re-deposited as the reddened non-pedogenic sediment layer at the Belmont\Rocky Bay contact, as was observed by Hearty (2002).

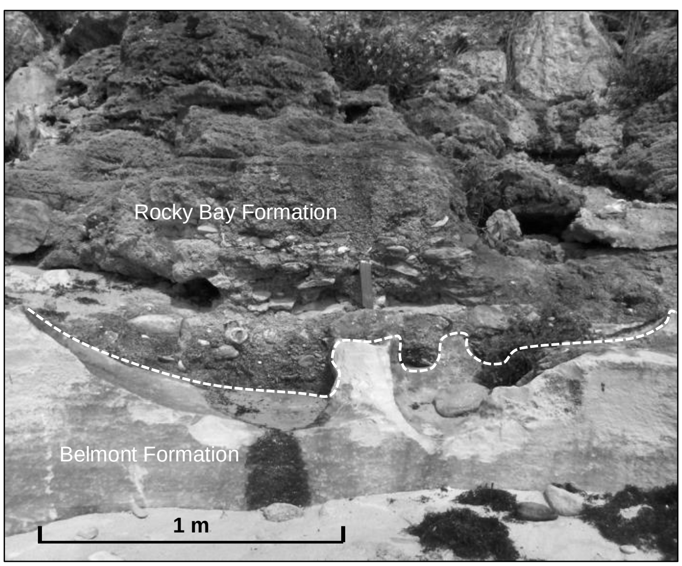


Figure 9. An unconformity correlative with the Shore Hills geosol. At this Grape Bay coastal exposure a Rocky Bay Formation conglomerate (above the broken white line) overlies heavily cemented Belmont shoreface deposits. The intervening Shore Hills geosol was stripped away by a MIS 5e transgression. The irregular Belmont Formation surface is partly attributable to erosion and partly to pedogenic/solutional processes. The evident contrast in diagenetic histories between the two formations is suggestive of a large time gap.

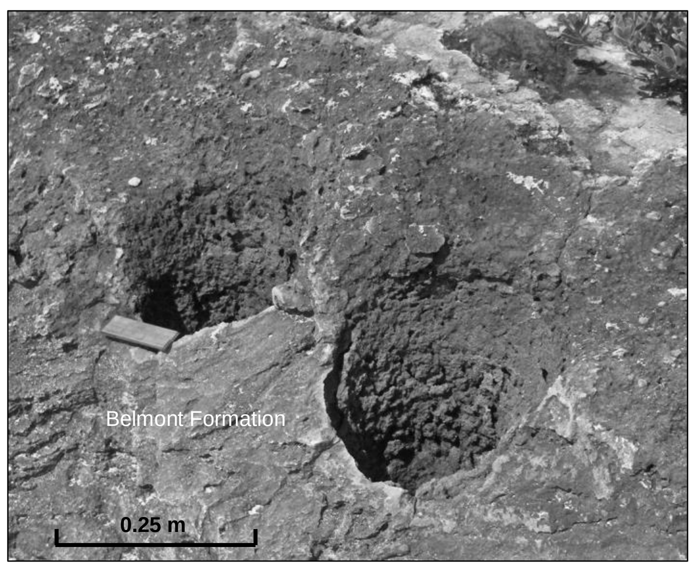


Figure 10. Solution pipes penetrating a Belmont Formation surface at Grape Bay. These structures are interpreted as pedogenic features associated with the "solutional unconformity" at the Belmont Formation/Rocky Bay Formation contact. They are remnants of the Shore Hills geosol which has been partially stripped away. Many of the "pipes" have an integral soil lining and, when seen in section, are frequently "bowl" or "cone" shaped which corroborates pedogenic origins, as opposed to them being tree trunk casts, which elsewhere are infilled with sand.

5.2 The stability of Bermuda

Quaternary Bermuda has long been characterised as isostatically (Harmon et al., 1978) and tectonically stable (Vacher, 1972, Harmon et al., 1983, Meischner et al., 1995, Ludwig et al., 1996, Hearty 2002 etc.). Tectonic instability typically is equated to crustal deformation as occurs at tectonic plate boundaries. Land et al. (1967) pointed to` the apparent absence of deformation on Bermuda, such as faulting or tilting, as proof of stability. The majority of researchers (spanning Sayles, 1931 to Hearty et al., 2007) thus shared the opinion that the Pleistocene sea level imprint on Bermuda was overwhelmingly glacio-eustatically controlled.

Vacher and Rowe (1997) first presented a case for the potential confounding effect of glacio-hydroisostasy at Bermuda; while Muhs et al. (2002), noted apparent evidence of the phenomenon in the form of anomalously elevated MIS 5a deposits at Fort St. Catherine (Figure 1). Notwithstanding an increasing acceptance of isostatic instability, the precept of "tectonic stability" has continued to be adopted (Dutton and Lambeck, 2012).

A default assumption of tectonic stablility at Bermuda has been questioned in the past (Peckenham,1981; Rowe 1998; and Bowen 2010). Features of Bermuda's geology which justify this doubt include: normal and reverse faulting (Figures 10 and 11) (see Supporting Information for a discussion);

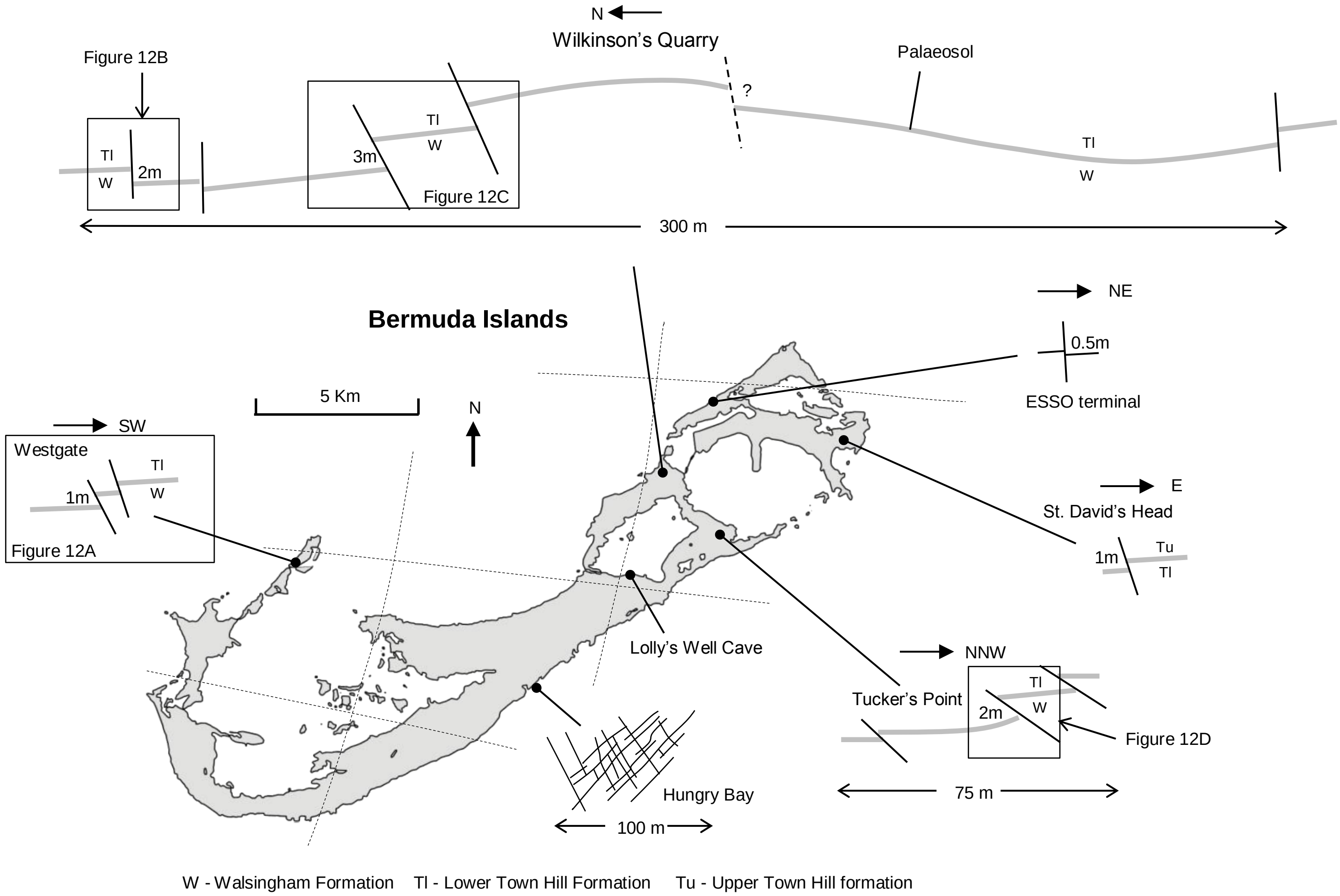
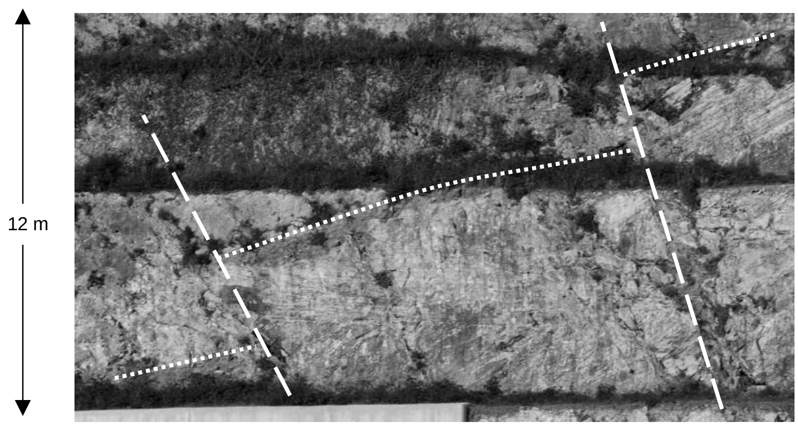


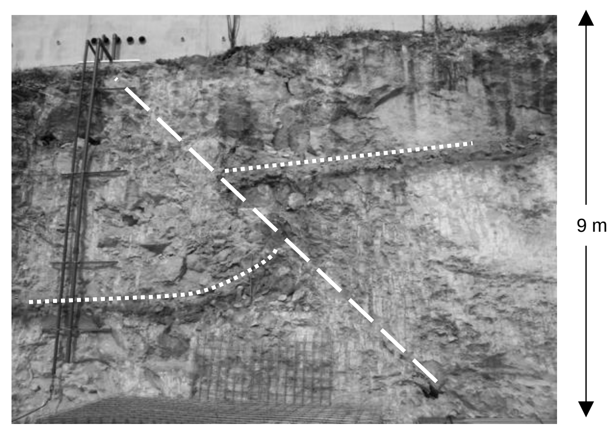
Figure 11. Location of Bermuda faults. Displacement geometries are shown, along with the alignment of the rock faces in which the faults are exposed. Fault strikes are not known with sufficient accuracy to plot on the map. Also shown (broken lines) are the stress trajectories inferred from joint/fracture orientations in Bermuda as plotted by Scheidegger (1976) who related the pattern to geotectonic stress in the North American plate. The joint system exposed in the seabed off Hungry Bay (shown in plan-view traced from aerial photos) has an orientation which is consistent with those documented on land by Scheidegger (1976) and Hartsock et al. (1995)

A. Westgate – reverse faults

B. Wilkinson's Quarry – normal fault



C. Wilkinsons' Quarry – reverse faults



D. Tucker's Point – reverse fault

Figure 12. Examples of normal and reverse faults in Bermuda's two oldest limestone formations - the Walsingham and Lower Town Hill Formations. See Figure 11 for locations.

rectilinear fracturing (Hartsock et al., 1995) that conforms to an orientation consistent with stress trajectories in the North American plate (Scheidegger 1976) (Figure 11); a history of idiosyncratic tectonic/isostatic behaviour of the Bermuda volcanic seamount, such that the expected subsidence (Clague and Moore, 2006) has been offset by uplift, as evidenced by ~30 million year old pillow lavas at shallow depths of ~-30m RSL where sub-aerial eruptives, or limestones, would typically be expected (Vogt and Jung, 2007); and anomalously high seismic activity within the Bermuda Rise (Zoback et al., 1986; Vogt and Jung, 2007).

That Bermuda is prone to earth tremors is well known to the inhabitants and that they can sometimes be powerful is attested to by a church record dated 1664 which describes "a great and fearful Earthquake which did shake Churches and Houses, Yea and the hearts of man too" (Bermuda Government archives). An unpublished record of earthquakes collated by Bermuda resident Dr.Martin Brewer catalogues a total of 56 earthquakes affecting Bermuda over the last 350 years. His analysis of the data reveals, for example, that those earthquakes which are defined as "moderate" on the Mercalli intensity scale (~> 4.3 Richter magnitude) have recurred at an average frequency of once every 11 years since 1842. The earthquake of 1664, mentioned in the church records, is considered by Brewer to have qualified as "destructive" with an estimated Richter magnitude of ~ 6.3.

The first reverse faults documented in Bermuda (Rowe, 1998) were a pair, with a combined displacement of 1.5 m, found at the entrance to Westgate Prison. At Wilkinson's Quarry, there is a system of reverse and normal faults, expressed as 1 to 3 m offsets of a palaeosol, extending over a 300 m north-south aligned rock. While, at Tuckers Point a series of low angle reverse faults exposed in a north-northwest trending rock face, displace a palaeosol by a total of >3 m (Figures 10 and 11). All of these faults are within the Quaternary Walsingham and Lower Town

Hill Formations (Bermuda's oldest two formations) but smaller faults and conspicuous fissuring occur throughout the stratigraphical column. Good accounts of fissure alignment in Bermuda and the potential association with stress trajectories in the North Atlantic plate (Figure 11) are provided by Scheidegger (1976) and Hartsock et al. (1995). More information about faulting in Bermuda, and a discussion of possible causes, is provided in the Supporting Information.

Also relevant to the question of Bermuda's stability, are the inconsistencies between published palaeo-sea-level curves reconstructed for Bermuda (e.g, Harmon et al., 1983; Hearty and Kindler, 1995) and palaeo-sea-level data from elsewhere. For example, whereas the +4.5 to +6 m RSL early MIS 5e imprint at Bermuda (Harmon et al., 1983; Vollbrecht and Meischner, 1996; Vacher and Rowe, 1997) is comparable with that at the Bahamas and many other intermediate and far field sites (Muhs et al., 2002), the MIS 5a imprint at ~ +1m RSL on Bermuda (Vacher and Hearty, 1989; Muhs et al., 2002) contrasts markedly with that of -15m, or lower, at the Bahamas (Richards et al., 1994) and at most far-field localities (Chappell and Shackleton, 1986; Schellmann and Radtke, 2004).

Mallorca is unusual in having a well-documented record of mid to late Pleistocene peak palaeo-sea-levels which approximates to that at Bermuda. MIS 7, MIS 5e and MIS 5a sea levels in the range of ~+1 to ~+5m RSL have been inferred from the ages and heights of phreatic overgrowths on speleothems in Mallorcan caves (Vesica et al., 2000; Dorale et al., 2010). Notably, Dorale et al. (2010) concluded that Mallorca, along with Bermuda, might be at respective pivot points between regions of glacio-isostatic emergence and submergence; and as a consequence, could have experienced sea levels which closely followed the eustatic curve. An alternative explanation is that unrelated sources of instability could have, coincidentally, produced similar relative sea level curves at both localities.

6 Conclusions

Three new MIS 7 ages, presented here, for coral fragments collected from the Belmont Formation, corroborate the two MIS 7 ages published by Muhs et al. (2002), and are entirely consistent with the established stratigraphy of Bermuda (Vacher et al., 1989). When combined with new sedimentological and fossil evidence, we conclude that MIS 7 relative mean sea levels at Bermuda exceeded the present level by at least 4.5 m, and probably reached or surpassed +6.0 m RSL. The MIS 7 maximum relative sea level at Bermuda is, thus, shown to be above the top of the range of eustatic palaeo-sea-levels, associated with that period, inferred from studies in most other parts of the world.

An anomalously high, late MIS 7 highstand at Bermuda is consistent with a lagging glacio-isostatic response at intermediate-field sites as predicted by glacio-isostatic adjustment (GIA) models (Dutton and Lambeck 2012; and Raymo and Mitrovica, 2012). The application of such models should, however, be undertaken with caution because of significant seismic activity around Bermuda and because of the existence of reverse and normal faulting in the islands' Quaternary limestones. The origin of these phenomena has yet to be determined; and until this is known, it is premature to conclude whether the contribution of the glacio-hydroisostatic palaeo-sea-level signal to the combined, predominantly eustatic, relative sea level curve is resolvable at Bermuda.

Bermuda has, in recent years, undergone a transition in the literature, from a eustatic "tide-gauge" to a glacio-hydroisostatic datum; both attributions having been predicated on the questionable assumption of tectonic stability. Calibration of new models, has in part relied on contentious palaeo-sea-level data sourced from previous publications. It is recommended that an objective re-evaluation be applied to other emergent marine-like deposits, on Bermuda, that have been linked to MIS 11, 5e and 5a highstands. In addition, other potentially more reliable sources of data should be explored, such as speleothem growth-interruptions or overgrowths; the use of which, for palaeo-sea-level research, was pioneered in Bermuda by Harmon et al., 1978. This should precede the incorporation of existing published age or elevation data, from Bermuda, into palaeo-sea-level models of global consequence.

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FIGURE CAPTIONS

Figure 1. Bermuda Islands locality map.

Figure 2. Mid to late Pleistocene stratigraphy of Bermuda in relation to palaeo-sea-level. The established consensus* version (A) includes the Belmont Formation deposited at a MIS 7 highstand. Hearty's (2002) version (B) re-allocates the "Belmont" deposits to the, MIS 5, Rocky Bay Formation and, correspondingly, downgrades the Shore Hills Geosol to an intra-formational colluvium. New age data, presented here, corroborates the former allostratigraphical model. * Sayles (1931), Bretz (1960), Land et al., (1967), Vacher (1972), Vacher et al., (1989), Vollbrecht and Meischner (1996), Vacher and Rowe (1997), Rowe (1998).

Figure 3. Examples of Belmont Formation facies sequences from Bermuda's south shore. The key sea-level indicator facies (SIFs) are considered to be: Hapm, Lapl, Trm, attributed, respectively, to the upper shoreface, foreshore and backshore environments (Figure 4). The SIFs at 1,2 and 3 record transitory positions of a generally rising relative sea level. Inter-tidal foreshore deposits at 1 are superseded, at the same or higher elevations, by sub-tidal shoreface deposits at 2,3 and 4. The highest imprint among these sequences, at Grape Bay (4), records a ~+4.5 m RSL sea level. Backshore flooding by storms or high tides is evidenced by water-lain Trm and Fln+f facies (5). A pause in, or reversal of, the trangression is represented by regressive Rof, Lal and Hapl sub-aerial facies.

Facies annotation breakdown: Ha - high angle cross strata (≥ 20°); La - low angle cross strata (< 20°); Fl – flat strata; Tr - trough shaped cross strata; p - planar strata; Ro - structureless; w - near symmetrical ripple cross strata; s - small scale cross strata set (< 5cm); m - medium scale cross strata set (5 cm – 1m) ; l - large scale cross strata set (> 1m).

Figure 4. Key sea-level indicator facies (SIF) of Bermuda's Belmont Formation. Hapm and Lapl are the products of wave action at the seaward front of a beach; whereas Trm developed in shallow flowing water which inundated the backshore during storms or at high tides. Their respective relationships to coeval mean sea level are inferred from modern equivalents in Bermuda and from analogous facies whose depositional environments have been reconstructed (by others) elsewhere in the world.

Figure 5. The Hapm facies in the Belmont Formation at Grape Bay. The sequence is interpreted as representing the progradation of a beach face (Lapl) and beach step (Hapm) over wave rippled upper shoreface deposits (Laws). Contemporaneous mean sea level stood at +3 to +4 m RSL. Not far to the west of this locality a +4 to +5 m RSL palaeo-sea-level is recorded by a similar sequence (Figure 7). The seaward increase in thickness of the Hapm facies is probably related to aggradation during beach progradation into slightly deeper water.

Figure 6. U-series ages of 35 coral fragments collected from progradational and aggradational foreshore and shoreface calcarenite deposits on Bermuda. Stated margins of error in the age measurements are < ±3 ka in all but three cases where they range up to ± 6 ka and in one case (the 262 ka age of Harmon et al., 1983) where it is > ±20.

Figure 7. A facies sequence , at Grape Bay, that represents progradation of the beach step (Hapm) over oscillation ripple cross laminae (Laws) of the upper shoreface (interpetation confirmed by email communication with Cristino Dabrio 2012). Intervening between the two are medium scale cross beds (wave ripples) of the inner rough facies (Clifton et al, 1971). A palaeo-sea-level of +4.0 to +5.0 m RSL is inferred. Oculina fragment "C" (bottom left) which yielded an age of 197 ka ±3 ka was found, nearby, at the base of the Hapm facies.

Figure 8. Emergent notch/palaeo-cliff, at Watch Hill Park, whose past partial submergence below mean sea level is evidenced by life-position bivalves (Brachidontes domingensis) and encrusting vermetid worms which would have occupied a high energy inter-tidal rocky shoreface. Boulders and marine sands which rest against the cliff are mapped as Belmont Formation marine deposits. Consistent with other evidence in the vicinity, such as high elevation phreatic cementation, these features are indicative of a Belmont highstand at of ≥ +6.0 m RSL.

Figure 9. An unconformity correlative with the Shore Hills geosol. At this Grape Bay coastal exposure a Rocky Bay Formation conglomerate (above the broken white line) overlies heavily cemented Belmont shoreface deposits. The intervening Shore Hills geosol was stripped away by a MIS 5e transgression. The irregular Belmont Formation surface is partly attributable to erosion and partly to pedogenic/solutional processes. The evident contrast in diagenetic histories between the two formations is suggestive of a large time gap.

Figure 10. Solution pipes penetrating a Belmont Formation surface at Grape Bay. These structures are interpreted as pedogenic features associated with the "solutional unconformity" at the Belmont Formation/Rocky Bay Formation contact. They are remnants of the Shore Hills geosol which has been partially stripped away. Many of the "pipes" have an integral soil lining and, when seen in section, are frequently "bowl" or "cone" shaped which corroborates pedogenic origins, as opposed to them being tree trunk casts, which elsewhere are infilled with sand.

Figure 11. Location of Bermuda faults. Displacement geometries are shown, along with the alignment of the rock faces in which the faults are exposed. Fault strikes are not known with sufficient accuracy to plot on the map. Also shown (broken lines) are the stress trajectories inferred from joint/fracture orientations in Bermuda as plotted by Scheidegger (1976) who related the pattern to geotectonic stress in the North American plate. The joint system exposed in the seabed off Hungry Bay (shown in plan-view traced from aerial photos) has an orientation which is consistent with those documented on land by Scheidegger (1976) and Hartsock et al. (1995).

Figure 12. Examples of normal and reverse faults in Bermuda's two oldest limestone formations - the Walsingham and Lower Town Hill Formations. See Figure 11 for locations.

Table 1. Ages of three Oculina fragments are provided versus the 1950 reference. 95% confidence intervals are quoted. Decay constants used are $9.1706 * 10^{-6}$ yr^{-1} for ^{230}Th, $2.822 * 10^{-6}$ yr^{-1} for ^{234}U (Cheng et al., 2013) and $1.55125 * 10^{-10}$ yr^{-1} for ^{238}U (Jaffey et al., 1971). Ages are corrected for detrital ^{230}Th assuming it is scavenged from seawater with an atomic ratio of ^{232}Th/^{230}Th of 20000 (Robinson et al., 2004).